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Neutral hydrogen in radio galaxies: results from nearby, importance for far away

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Abstract. The study of neutral hydrogen emission and absorption in radio galaxies is giving new and important insights on a variety of phenomena observed in these objects. Such observations are helping to understand the origin of the host galaxy, the effects of the interaction between the radio jet and the ISM, the presence of fast gaseous outflows as well as jet-induced star formation. Recent results obtained on these phenomena are summarized in this review. Although the H I observations concentrate on nearby radio galaxies, the results also have relevance for the high-z objects as all these phenomena are important, and likely even more common, in high-redshift radio sources.

Key words: galaxies: active – galaxies: ISM

1. Introduction: what can we learn from the H I in nearby radio galaxies

There are a number of important aspects of radio galaxies that can be investigated using observations of neutral hydrogen. Because of sensitivity limitations of present day radio telescopes, some of these studies are restricted to nearby radio galaxies. Nevertheless, they can give important insights on phenomena that are likely to be very common in high redshift objects. Here I summarize some recent results obtained for low-z radio galaxies, underlining their relevance for galaxies in the far away Universe.

Hierarchical (major) merging and accretion of small clumps appears to be a good description of the formation of early-type galaxies, i.e. the typical host of radio galaxies (see Fig. 1, Mihos 1999). If this is the case, the presence and morphology of extended H I can be used as tracer to investigate the origin and evolution of these galaxies. This is particularly interesting in the case of radio galaxies as the origin of activity in galaxies is often explained as triggered by merger and/or interaction processes. Torques and shocks during the merger can remove angular momentum from the gas in the merging galaxies and this provides injection of substantial amounts of gas/dust into the central nuclear regions (see e.g. Mihos & Hernquist 1996). Indeed, this appears to be the case for radio galaxies as suggested by morphological and kinematical evidence (e.g. Heckman et al. 1986; Tadhunter et al. 1989).

Another aspect that can be investigated using the neutral hydrogen is the effect of the interaction between the radio plasma and the interstellar medium (ISM) that surrounds the radio source. Indeed, the phase of nuclear activity is now increasingly recognized to play an important role in the evolution of the galaxy itself. Particularly important in this respect are gas outflows that can be generated by this activity and the effect they can have on the ISM. This feedback can be extremely important for the evolution of the galaxy, up to the point that it could limit the growth of the nuclear black-hole (e.g. Silk & Rees 1998; Wyithe & Loeb 2003). Thus, the processes of assembly of the host galaxy, the supply of gas to the central region, as well as the effects that the triggering of the (radio) activity has on this gas, are tightly related and essential for our understanding of radio galaxies. An other aspect related to the interaction is the possibility of jet-induced star formation, a phenomenon considered to be particularly relevant for high-z radio galaxies.

2. Large-scale H I (emission) in nearby early-type galaxies

Large-scale H I (in emission) around galaxies hosting radio sources provides an important signature of whether a (major) merger has occurred in the life of these galaxies. More details

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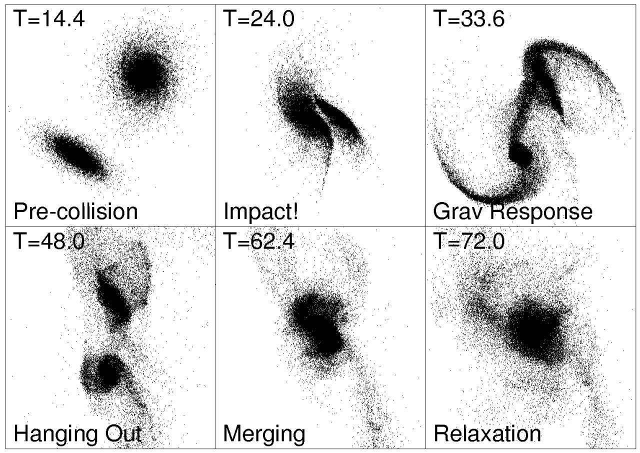

Fig. 1. Numerical simulations of major mergers resulting in an elliptical galaxy (from Mihos 1999).

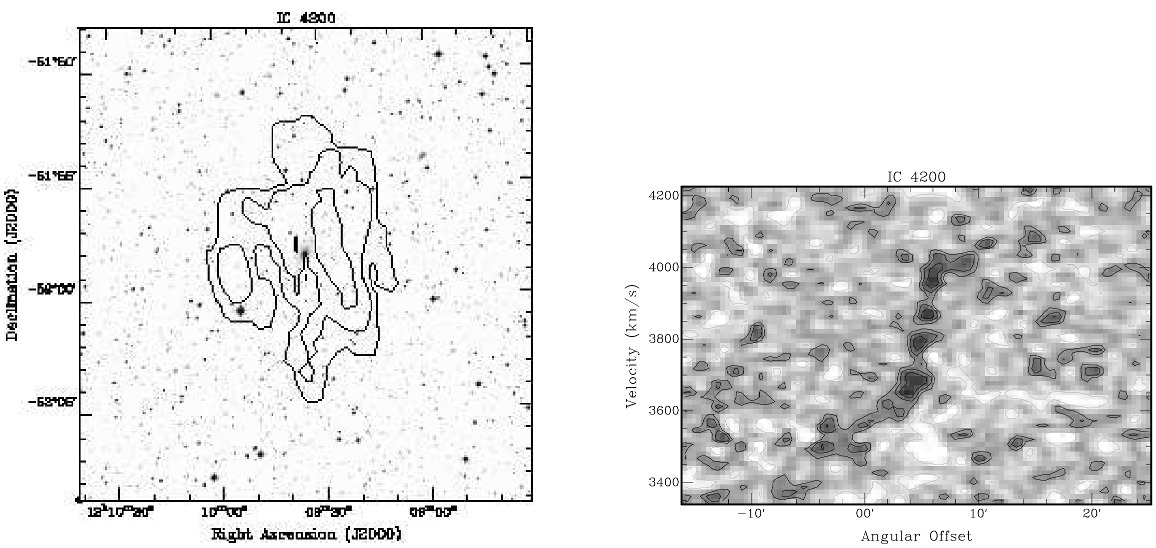

Fig. 2. Total intensity (left) and position-velocity plot along the major axis (right) for the early-type galaxy IC 4200. The H I disk is about 200 kpc in size. Contour levels are: $2, 4, 8, 16 \times 10^{19}$ cm^{-2} (left) and -3, 3, 6, 8 mJy beam^{-1} (right).

about the results of this study are presented in Emonts et al. (these Proceedings). However, to put these results in the more general context of the formation and evolution of early-type galaxies, we describe first the results obtained on the occurrence and morphology of the neutral hydrogen in "normal" early-type galaxies. These results will be later (Sec 2.3) compared with what found for radio galaxies.

2.1. Shallow surveys

It is already known since many years that HI-rich early-type galaxies do exist (e.g. Knapp et al. 1985; Morganti et al. 1997; van Gorkom etal. 1997; Oosterloo et al. 2002). More recently, however, a systematic, albeit shallow, H I survey of all early-type galaxies south of $\delta < -25°$ with $V < 6000$ km s^{-1} (based on the Parkes All Sky H I Survey: HIPASS, Barnes et al. 2001 and followed up with the ATCA, Oosterloo et al. in preparation) has revealed that in most of these H I-rich early-type galaxies the H I is distributed in very large (up to 200 kpc in size), regular disks of low column density H I. Fig. 2 shows the case of IC 4200. *The amount of H I and the size of the structures can be explained as result of major mergers between gas-rich disk galaxies.* This is indeed how at least some early-type galaxies are believed to be formed (see e.g. the case of NGC 7252, Hibbard & van Gorkom 1996).

As mentioned above, this survey is shallow, therefore able to detected only galaxies with associated more than $10^9\ M_\odot$ of neutral hydrogen. Nevertheless, the results are telling us not only that such large amount of neutral hydrogen (with H I masses up to $10^{10}\ M_\odot$ and log $M_{\rm HI}/L_B$ is between -1 and 0 for the H I detected galaxies) appear to be present around 5-10% of early-type galaxies but also that, because of their regular and large appearance, these disks must be quite old, in many cases well over 5×10^9 yr. Hence, they are not related to recent accretions. The H I column density in these disks peaks at only 10^{20} atoms cm^{-2} (i.e. 0.5-1 M$\odot$/pc^2). Thus, despite the large H I reservoir, no significant star formation is occurring, therefore the HI is not used and the H I

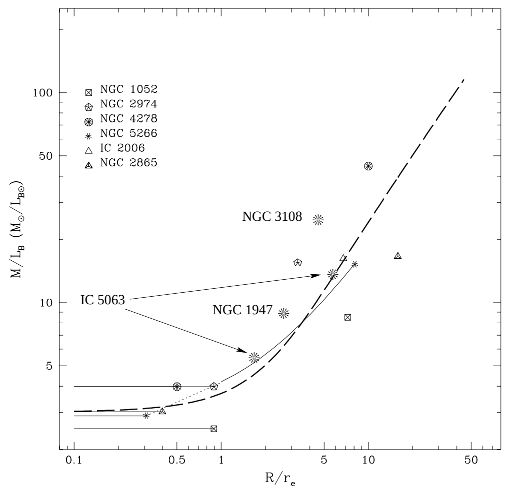

Fig. 3. The log(M/L_B) - log(R/R_e) diagram (modified from Bertola et al. 1993). The dashed thick line represents the cumulative M/L_B as function of radius for spiral galaxies. The symbols represent the data for the elliptical galaxies obtained from the optical and the H I data. From Morganti et al. 1999.

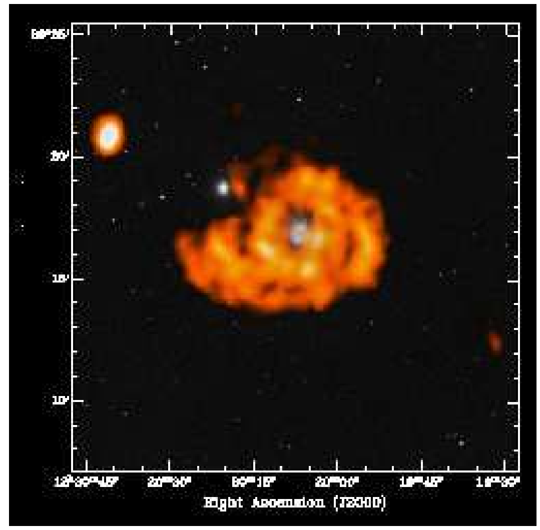

Fig. 4. WSRT total H I intensity (orange) of the galaxy NGC 4278 superimposed to the optical image (grey).

disks will evolve only very slowly. Finally, these large, regular structures can be used to get information about the dark matter content of early-type galaxies. So far it appears that this is similar to what found in spirals galaxies (see Fig. 3).

2.2. Deep H I-search

The shallow surveys described above have shown that H I-rich early-type galaxies do exist. However, it is also important to investigate how common is, around these galaxies, the presence of (even a modest amount of) neutral hydrogen and what are its characteristics. To investigate this, a representative sample of 12 early-type galaxies has been observed using the WSRT. These galaxies were selected because they are part of the sample studied in the optical with the SAURON panoramic integral-field spectrograph on the William Herschel Telescope, La Palma. SAURON provides a very detailed view of the kinematics of the ionised gas and of the stellar component in the inner regions of these objects (de Zeeuw et al. 2002).

This deep, albeit so far small, survey can detect H I masses down to $< 10^7$ M$_\odot$. In nine of the 12 objects observed (75%) H I associated with the galaxy has been detected (Morganti, de Zeeuw, Oosterloo et al. 2005a). This finding indicates that *neutral hydrogen appears to be a common characteristic of these galaxies, provided that deep enough observations are available.* The neutral hydrogen shows a variety of morphologies, from complex structures (tails, offset clouds) to regularly rotating disks. Four of the detections belong to the latter group and they will be the main test cases for probing the dark matter content in the inner and outer part of the galaxies in a consistent way. The most extreme case in our sample is a gas disk of only 2×10^6 M$_\odot$ and a column density of 5×10^{18} cm^{-2} that has been found in the young SO galaxy NGC 4150.

Figure 4 shows the results for the elliptical galaxy NGC 4278. This galaxy has an H I disk that extends well beyond the optical image. The velocity maps of the ionised gas and of the stars (as obtained with SAURON) together with the velocity map of the H I illustrate one of the recurrently found characteristics: the kinematics of the H I is very similar to that of the ionised gas, indicating that they form one single structure. This is underlined by the fact that galaxies with little or no ionised gas are less likely to show H I. In NGC 4278, an offset exists between the position angle of the rotating gas disk (H I and ionised) and that of the rotation of the stars, something that is observed in several cases and may reflect the non-axisymmetric nature of the galaxies. These offsets in kinematic alignment can vary from co- to counter-rotating, sometimes showing dramatic twists within a single object.

2.3. H I in nearby Radio Galaxies

The results presented above have been obtained for samples of "normal" early-type galaxies, therefore not biased toward radio-loud objects. A study of H I in radio galaxies has been instead carried out by Emonts et al. (in prep). The sample includes more than 20 objects (both in the northern and in the southern hemisphere). The selection and observations of the northern sample are described in Emonts et al. (these proceedings). The H I mass limit of this survey is somewhat in between the surveys described above (few time 10^7 up to 10^8 M$_\odot$) and therefore the comparison between them is difficult. Among the radio galaxies, 25% of the objects are detected in H I in emission. Interestingly, the most H I-rich objects (again with H I masses up to 10^{10} $M_\odot$ and log M$_{\rm H\,I}$/L$_B$ is between -1 and 0) have the neutral hydrogen distributed in very large disks with regular kinematics as found in the shallow survey described in Sec. 2.1. An example of an extended disk of H I around a radio galaxy is shown in Fig. 5. Thus, as for those galaxies, the origin of the large amount of H I is likely to be major mergers of gas-rich disk galaxies. The formation of regular disk structures is explained in numerical simulations

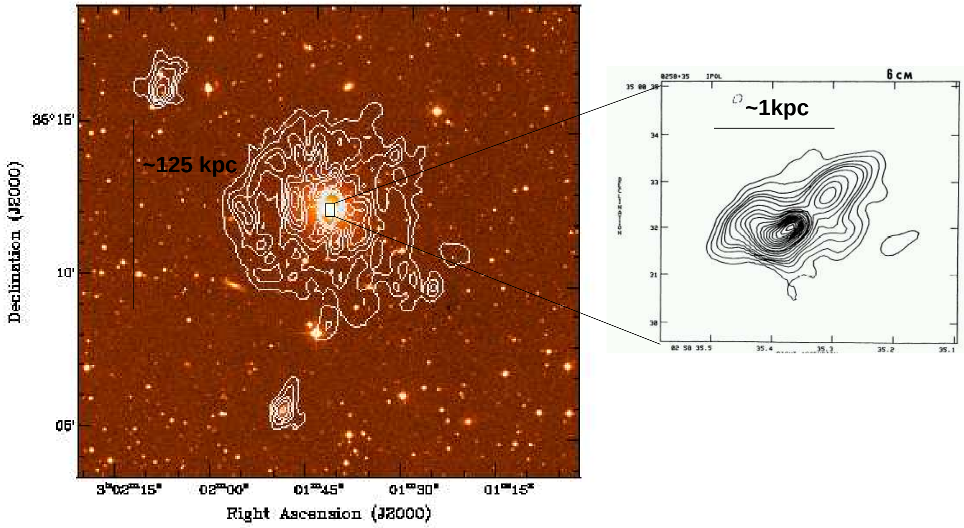

Fig. 5. *Left* H I total intensity (contours) superimposed to an optical image of B2 0258+35 (from Emonts et al. in preparation). *Right* The continuum image (from Fanti et al. 1986).

as result of merger of similar size galaxies (from 1:1 to 1:4) with high angular momentum (Barnes 2002; Burkert & Naab 2003). The gas from the progenitors falls back at a late stage of the merger (after the starburst phase) and settles in a disk. The combination of H I and study of the stellar population (in progress) allows to put the AGN activity in the evolutionary sequence of early-type galaxies (see the case of B2 0648+27 in Emonts et al. these Proceedings).

Other radio galaxies appear to have a much smaller amount of H I (with H I masses between 10^8 and 10^9 $M_\odot$ and log $M_{\rm H\,I}/L_B$ is between -2 and -1) and the neutral hydrogen is either distributed in disks or in blobs or tails. These objects appears to be more similar to what found in the deep SAURON survey (see Sec. 2.2). Thus, although the comparison is not completely fair and based on small numbers statistic, we do not find so far major differences in the H I characteristics (detection rate, morphologies, masses, etc.) between "normal" early-type and radio galaxies. This may indicate that indeed the radio-loud phase is just a short period in the life of many (all?) early-type galaxies. However, it should be noticed that in our sample of radio galaxies all the large H I disks have been detected so far around compact radio sources, see Fig. 5 for an example. The reason for this is not yet clear. Some possible explanations are given in Emonts et al. (these Proceedings).

Finally, we would like to point out possible similarities between the large quiescent Lyα structures detected in high-z galaxies (Villar-Martín et al. 2002, 2005 in these proceedings) and the large H I disks detected in low-z radio galaxies.

3. Jet-induced star formation

As shown above, the host galaxies of radio-loud AGN can be gas rich. Thus, the interaction between the non-thermal plasma ejected from the active nucleus and the ISM of a galaxy can have important consequences and can be responsible for a variety of phenomena in radio galaxies such as ionisation of the gas, AGN driven outflows and jet-induced star formation. Such interactions are considered to be particularly relevant in high redshift radio galaxies, as they are typically living in a gas-rich environments (see e.g. van Breugel 2000 and references therein). As mentioned above, one aspect of jet-ISM interaction is that it can trigger star formation and this is considered a possible mechanism to explain the UV continuum emission observed in the host galaxies of distant radio sources and the "alignment effect" between the radio emission and this continuum (Rees 1989). Detecting and studying star formation produced by this mechanism in high-z radio galaxies is very challenging. The only case where this has been done is 4C 41.17 (Dey et al. 1997). Because of the observational problems for high-redshift sources, it is important to find nearby examples of star formation triggered by the radio jet that can be studied in more detail. The nearby, best examples are Centaurus A (Oosterloo & Morganti 2005) and the Minkowki's Object (van Breugel et al. 1985).

3.1. Jet-induced star formation in Centaurus A

In the case of Centaurus A, new 21-cm H I observations of the large H I filament located about 15 kpc NE from the centre of this galaxy and discovered by Schiminovich et al. (1994) have been carried out using the ATCA (Oosterloo & Morganti 2005). This H I cloud is situated (in projection) near the radio jet of Centaurus A (see Fig. 6), as well as near a large filament of ionised gas of high excitation and turbulent velocities and near regions with young stars. The higher velocity- and spatial-resolution of the new data reveal that, apart from the smooth velocity gradient corresponding to the overall rotation of the cloud around Centaurus A (Schiminovich et al. 1994), H I with anomalous velocities up to 130 km s^{-1} is present at the southern tip of this cloud (see Fig. 6 and Oosterloo & Morganti 2005). This is interpreted as evidence for an ongoing interaction between the radio jet and the H I cloud. Gas stripped from the H I cloud gives rise to the large filament

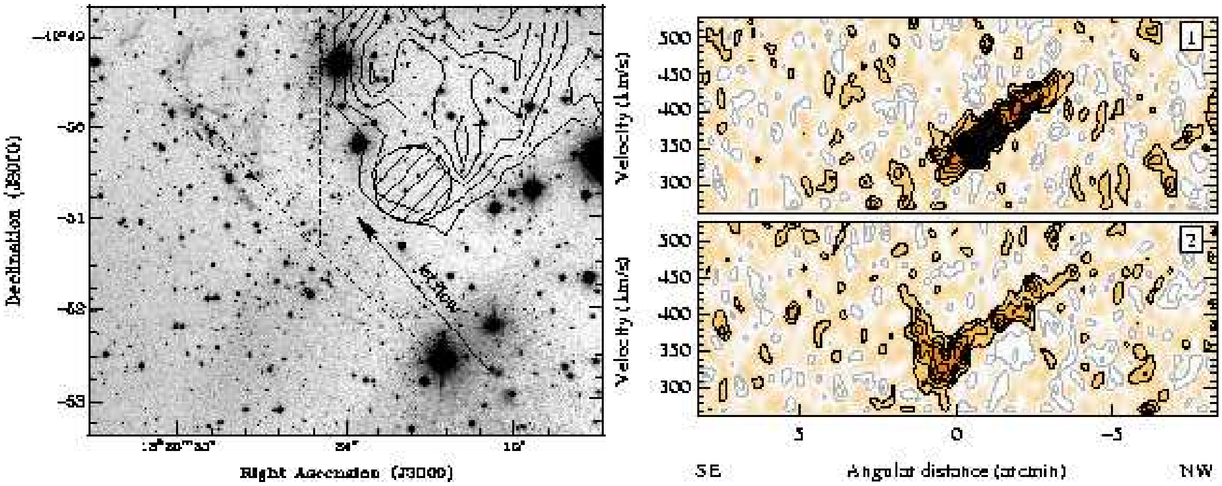

Fig. 6. *Left* H I contours of the southern region of the H I cloud, drawn on top of a broad band optical image (kindly provided by M. Rejkuba). The hatched area indicates the location where the anomalous H I velocities are detected while the arrow indicates the location and the flow direction of the radio jet. The filament of ionised gas is visible in the top left. The dashed lines roughly indicate the locations of young stars. *Right* Position-velocity plots taken through the location of the anomalous H I (bottom) and, for comparison, taken just above that region (top). Taken from Oosterloo & Morganti (2005).

of ionised gas and the cooling of the gas is then responsible for the star formation regions that are found downstream from the location of the interaction. From the displacement of the young stars from the location of the anomalous velocities we derive a flow velocity of about $100\,\mathrm{km\,s^{-1}}$, very similar to the observed anomalous H I velocities.. The jet induced star formation appears to be fairly inefficient, of the order of few percent. Recent numerical simulation have shown that radio jets can indeed drive radiative shocks in interstellar clouds, causing them to compress and break up into numerous dense, cloud fragments. These fragments survive for many dynamical timescales and are presumably precursors to star formation (Mellema et al. 2002; Fragile et al. 2004).

3.2. Jet-induced Star Formation in “Minkowski’s Object”

Minkowski’s Object is a peculiar starburst galaxy (at z = 0.0187) at end of the jet from NGC 541 (van Breugel et al 1985; van Breugel et al. 2004; Croft et al. 2004). This object is an ideal candidate for a detailed study of the effects of the interaction between the radio plasma and the ISM. Its morphology is strongly suggestive of a collision of a low luminosity FR-I type jet from NGC 541 with a gas rich cloud/object (see Fig. 7 and van Breugel et al. 1985).

Recent C-array VLA observations have shown that a cloud of H I is detected just down-stream from the main star formation region (see Fig. 7). This cloud has a total H I mass of $\sim 3 \times 10^8$ $M_\odot$ (corresponding to a $M_{\rm H\,I}$/ $L_B \sim 0.17$), it has the same transverse size as the radio jet and consists of two main components separated at the centre of the radio jet. A velocity gradient in the H I of ~ 60 $\mathrm{km\,s^{-1}}$ is observed.

Although, as in the case of Centaurus A, H I is detected close to the location of the star formation and radio jet, it is not clear whether the same scenario can explain the case of the Minkowski’s Object. In this object the radio jet itself may be the cause of the formation of the H I as predicted in the jet-triggered radiative cooling model (Fragile et al. 2004). This model shows that star formation, and the H I that preceeds this, can occur in relatively warm gas due to radiative cooling triggered by the radio jet. However, until stronger constrains to this model will be available from new, higher resolution H I observations the possibility that the origin of the starburst is instead due to a pre-existing peculiar galaxy or a pre-existing cold gas (like in the case of Centaurus A) cannot be ruled out.

3.3. Results from jet-induced star formation

The kinematic of the H I supports the idea that at least in two nearby objects (Centaurus A and Minkowski’s Objects) radio jets can trigger star formation. In both cases, H I is observed in regions where jet-induced star formation has been claimed to be present. The kinematics of the neutral hydrogen, its morphology and its relation to ionized gas give constraints on the on-going process. The next step will be a more detailed comparison between the results from the observations (in particular from high resolution H I data) and the results from numerical simulations. Because the gas densities and the AGN activity are higher in early Universe, jet-induced star formation is, therefore, likely to be a more common phenomenon in high-z radio galaxies.

4. Fast H I outflows

Gaseous outflows appear to be a widespread phenomenon in galaxies, both in the local as well as in the far-away Universe (e.g. Crenshaw et al. 2003; Veilleux et al. 2005; Frye et al. 2002). They can be driven by super-winds in the starburst phase or by the energy released in the active phase of the nucleus. AGN-driven outflows of ionized gas have been detected in many nearby galaxies. These outflows are a key in-

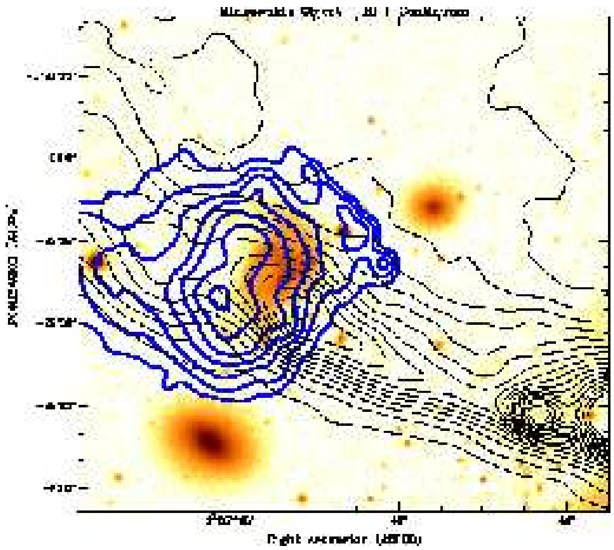

Fig. 7. C-array H I cloud (thick, blue contours) at the end of the radio continuum jet (thin, black contours) superimposed onto a Keck image of the Minkowski's Object (van Breugel et al. in prep).

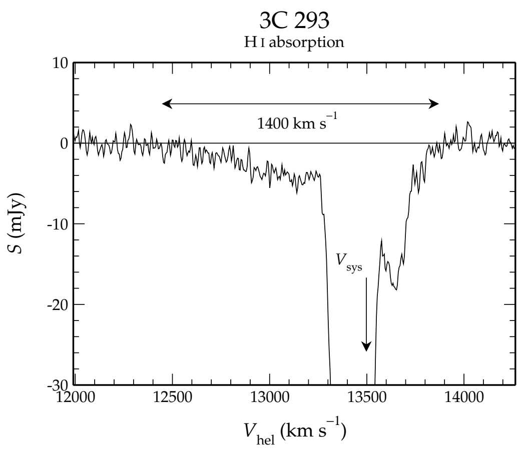

Fig. 8. A zoom-in of the H I absorption spectra of 3C 293 clearly showing the broad H I absorption. The spectra are plotted in flux (mJy) against optical heliocentric velocity in km/s. From Morganti et al. 2003.

gredient in galaxy evolution. The correlation found between the mass of the super-massive black-hole and the mass of the central bulge of the galaxy are most easily understood in terms of feedback models (Silk & Rees 1998). Numerical simulations suggest that the energy released by a quasar expels enough gas to quench both star formation and further black-hole growth (e.g. di Matteo, Springel, Hernquist 2005).

Recent results underline the importance of radio jets in producing such outflows. These outflows have been found not only associated with ionized gas (see Tadhunter these Proceedings) but also with neutral hydrogen. Recent sensitive, broad-band 21-cm observations of the radio sources IC 5063 (Oosterloo et al. 2000) and 3C 293 (see Fig. 8; Morganti et al. 2003; Emonts et al. 2005) have revealed that fast outflows of neutral hydrogen can occur in galaxies with an AGN. In addition to these two initial objects, more cases of broad and blueshifted H I absorption have been found using very sensitive and broad-band 21-cm radio observations with the Westerbork Synthesis Radio Telescope. Thus, fast and massive outflows may be common, in particular in young powerful radio sources (Morganti et al. 2005b). Interestingly, the mass outflow rates detected for the neutral gas are much larger than those typically found for the ionised gas and are large enough to have a significant impact on the evolution of the galaxies. The WSRT broad band covers ± 2000 km s^{-1} around the central velocity (systemic velocity of the galaxy). The observed borad H I absorption features have a width up to 2000 km s^{-1} and a typical optical depth $<< 1\%$, corresponding to a column density few times 10^{21} cm^{-2} (for T_{spin} = 1000 K) The detected H I absorption features are mostly blueshifted therefore corresponding to gas outflows. In order to understand the origin of such fast outflows it is important to know the location where the outflow is occurring.

4.1. The case of 3C 305

High-spatial resolution 21-cm H I VLA observations were obtained for the radio galaxy 3C 305 (Morganti et al. 2005c). These new high-resolution data show that the ~ 1000 km s^{-1} broad H I absorption, earlier detected in low-resolution WSRT observations, is occurring against the bright, eastern radio lobe, about 1.6 kpc from the nucleus (see Fig. 9).

We also used new optical spectra taken with the WHT to make a detailed comparison of the kinematics of the neutral hydrogen with that of the ionised gas (see Fig. 10). The striking similarity between the complex kinematics of the two gas phases suggests that both the ionised gas and the neutral gas are part of the same outflow. Earlier studies of the ionised gas (Heckman et al. 1982; Jackson et al. 2003) had already found evidence for a strong interaction between the radio jet and the ISM at the location of the eastern radio lobe. These results show that the fast outflow produced by this interaction also contains a component of neutral atomic hydrogen. The most likely interpretation is that the radio jet ionises the ISM and

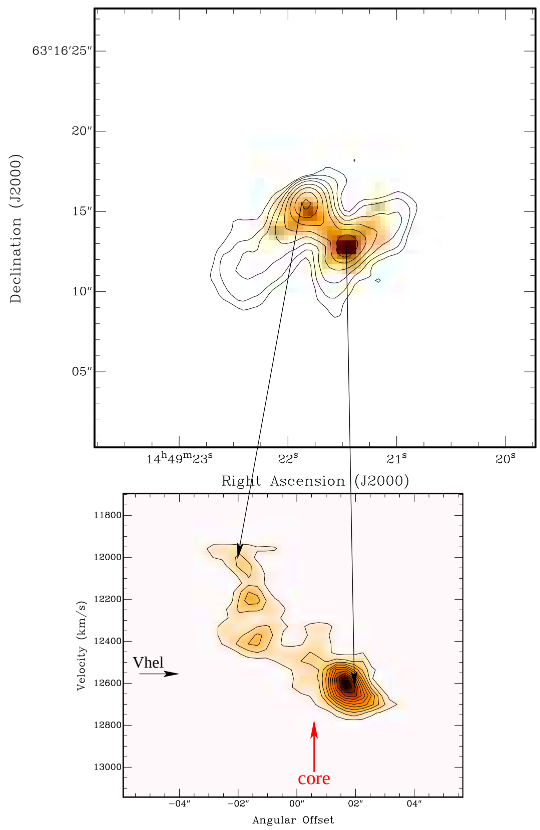

Fig. 9. Panel showing *(top)* the radio continuum image of 3C 305. *(Bottom)* The position-velocity plot from a slice passing through the two lobes. The broad H I absorption is detected against the NE radio lobe, about 1.6 kpc from the nucleus. The contour levels for the continuum image are 10 mJy beam^{-1} to 830 mJy beam^{-1} in steps of a factor 2. The grey scale image represents the total intensity of the H I absorption. The contour levels of the H I are -0.7, ..., -7.7 mJy beam^{-1} in steps of 0.7 mJy beam^{-1}. The arrow represents the systemic velocity. Taken from Morganti et al. (2005c)

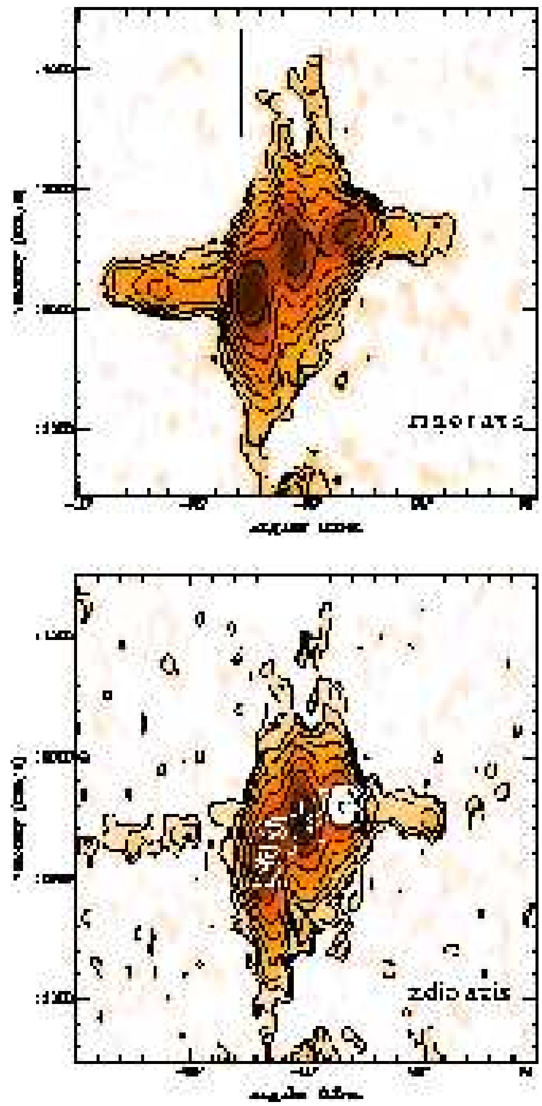

Fig. 10. *Top* WHT spectrum of the [O III] region of 3C 305 (after the subtraction of the continuum from the galaxy) taken in p.a. 60°, i.e. along the galaxy's major axis (NE to the left, SW to the right). The two arrows represent the approximate position of the peak of the radio lobes. *Bottom* WHT spectrum of the [O III] region of 3C 305 (black contours and grey scale) taken in p.a. 42°, i.e. along the radio axis. White contours represent the H I position-velocity plot taken along the radio axis (as in Fig. 9).

accelerates it to the high outflow velocities observed. These observations demonstrate that, following this strong jet-cloud interaction, not all gas clouds are destroyed and that part of the gas can cool and become neutral. The mass outflow rate measured in 3C 305 (but also in other objects, see below) is comparable, although at the lower end of the distribution, to that found in Ultra Luminous IR galaxies. This suggests that AGN-driven outflows, and in particular jet-driven outflows, can have a similar impact on the evolution of a galaxy as starburst-driven superwinds.

4.2. Results from fast H I outflows

The results obtained so far show that fast outflows of neutral hydrogen can be produced by the interaction between the radio jet and the surrounding dense medium. The presence of neutral gas in these regions indicates that the gas can cool very efficiently following a strong jet-cloud interaction. Interestingly, the associated mass outflow rates range from a few tens to about almost hundred $M_\odot$ yr^{-1}, comparable to (although at the lower end of the distribution) the outflow rates found for starburst-driven superwinds in Ultra Luminous IR Galaxies (Rupke et al., 2002; Heckman 2002). Thus, as these superwinds, the massive, jet-driven HI outflows in the radio-loud AGN can have a major impact on the evolution of the host galaxy. High-z H I absorbers have been also found in Lyα profiles (although with lower column density). As for the low-z cases, a possible way to explain these absorptions is via highly supersonic jet expanding into the dense medium of a young radio galaxy that then will be surrounded by an advancing quasi-spherical bow shock (Wilman et al. 2003; Krause 2002). Thus, the detailed results obtained for

the nearby objects can help in understanding better the mechanism at work in their far away cousins.

5. Conclusions

This review aimed to illustrate the importance that studies of the neutral hydrogen can have for the understanding of different phenomena observed in radio galaxies. In nearby radio galaxies, the H I is beginning to tell us about the origin of the host galaxy and about the presence and location of fast gaseous outflows, that appear to have a significant impact on the evolution of the galaxy. Nevertheless, despite the recent progress, a number of questions remain still open. For example: what is the link (if any) between large H I disks (low-z) and quiescent Lyα structures (high-z)? what are the details of the physical process that produces fast H I outflows? How common/important is the jet-induced starformation at high-z (and at low-z)?

Unfortunately at present deep studies of the neutral hydrogen as presented in this review are only limited to nearby galaxies. The need for the new generation of radio telescopes, and in particular for the Square Kilometer Array is clear. A detailed overview of what this new instrument will do for us can be found in the “SKA Science Case” (Carilli & Rawlings 2004). Hopefully we do not only have to wait for SKA but we may have some answers to these questions before the next meeting!

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